Appendix D. Seismic Design and Qualification of ESF Air Cleaning Systems[1]

D.1 INTRODUCTION

External components of the system (e.g., ducts, housings, and fans), insofar as practicable, should be rigidly anchored to major building elements (walls, floors, partitions). These building elements have sufficient stiffness that it can be assumed that the interaction of the air cleaning system on the building is negligible, and that the motion of the building element can be considered as the only input to the system. Where this type of anchoring is not practicable (e.g., as with ductwork), lateral bracing or other means to minimize movement of the external component must be provided. External components of the same system should be anchored to the same building element. Where this is not possible, the motion produced in the building element experiencing the greatest motion under the influence of an earthquake should be used to determine the accelerations of all segments of the system or subsystem. When parts of the system are anchored to more than one building element, displacements of the anchor points of different parts of the system should be considered as 180° out of phase and must be added to establish the maximum stresses in connections and other parts of the system that could be affected by the differential loading. Connections and anchors must be designed to accommodate simultaneously the combined horizontal, vertical, twisting, and bending motions. Expansion joints, expansion loops, or other means of providing flexibility while preserving the leak integrity of the system, may be used where necessary.

Anchors, attachments, and connections between runs of duct, dampers (valves), and fans (including motor and motor mount), must be designed to transmit the forces associated with the accelerations induced in the air cleaning system and the relative distortions of the building elements to which the external components of the system are anchored. Ducts and housings (including their pressure boundary welds and flanged connections), and filter mounting frames and doors (including door frames) of housings, should be designed to withstand, without buckling or rupture, the forces associated with equipment accelerations, relative distortions of connected parts, and relative distortions of building elements to which they are anchored.

1. N. J. Mason and P. J. Lama, "Seismic Control for Floor Mounted Equipment," *Heat. Piping Air Cond.* 48(3), 97–104 (1976).

D.2 COMPONENT QUALIFICATION

Maximum accelerations, displacements, and relative-velocity changes that can be tolerated by manufactured components (fans, filters, adsorbers, dampers, etc.) without damage or failure of function should be determined as a function of frequency by the manufacturer or the system designer. Qualification may be either by testing in accordance with Sect. D.4 or mathematical analysis in accordance with Sect. D.5 if possible. A component vulnerability spectrum should be prepared from the test or analytical data to show the maximum displacements and accelerations that the equipment can tolerate, as a function of frequency, without damage or loss of function. Qualification of the equipment may be based on either (1) comparison of the component vulnerability spectrum with the response spectrum of the building element to which the component is anchored or (2) demonstration of the operability of the equipment following the test. Natural frequencies of the equipment, installed and operated as it will be in service, should be determined if possible, but may be ignored if proven to be less than 0.3 Hz or greater than 30 Hz.

D.3 BUILDING-ELEMENT RESPONSE SPECTRUM

The designer should be furnished with or should compute, for each building element of interest, the maximum accelerations, displacements, and relative velocity changes, as a function of frequency, that can be expected in the building element as a result of the design basis earthquake.

D.4 TESTING

Components or the complete system may be qualified by testing under simulated earthquake conditions. The item to be tested is mounted on a biaxial or triaxial vibration generator in a manner that simulates the intended service mounting, and vibratory motion is applied independently to each of the perpendicular axes. Displacement induced in the vertical axis should be considered to be at least 0.67 times the displacement in the major horizontal axis. The magnitudes of horizontal acceleration and displacement are those magnitudes for which the item is to be qualified. Where practicable, it is recommended that the accelerations, displacements, and relative velocity changes be the maximums which the equipment can tolerate without loss of function. For fans, motors, dampers, and other operating devices, sufficient monitoring devices must be used to thoroughly evaluate performance during and after testing; monitoring devices must be located on the equipment or test assembly so that the maximum response is always obtained. Test are made at several sinusoidal frequency steps representative of the range of frequencies for which the item is to be qualified, at the natural frequency, or at a number of predetermined frequencies as outlined below.

D.4.1 Exploratory Vibration Test

An exploratory test should first be made, using a sinusoidal steady-state input of low magnitude, to determine the presence and location of any natural frequencies within the range of 0.1 to 60 Hz, or the frequency range stated in the project specification. The test should include a minimum of two sweeps at a maximum sweep rate of 2 Hz and a minimum acceleration of 0.1 g, with dwell at resonance for at least 30 sec and dwell for 1 min at each natural frequency. If no resonating frequencies are found, the item may be analyzed statically or may be tested (1) by a continuous test (Sect. D.4.2), (2) by sine-beat test (Sect. D.4.3), or (3) by a multiple-frequency test (Sect. D.4.4).

If one or more resonant frequencies are found in the exploratory test, the design of the component should, if possible, be modified to move the resonating frequencies above 30 Hz or the maximum frequency for which the item is to be qualified, then tested in accordance with Sect. D.4.2. If the item cannot be readily modified, a performance test should be made at the resonant frequency at an amplitude of at least the corresponding value for that frequency from the response spectrum for the building element of interest.

Items having resonance frequencies below 5 Hz require special consideration because available vibration generators may not be adequate to produce the required dynamic forces. The item may be modified to increase the resonating frequency to a level where testing by the sine-beat method is possible; otherwise, sufficient testing and analysis must be carried out to verify the structural and functional integrity of the item.

D.4.2 Continuous Test

A continuous sinusoidal motion corresponding to the maximum acceleration to which the item is to be qualified, at the frequency for which the item is to be qualified, is imposed for a length of time conservatively consistent for the service for which the item will be used, during which the item is operated to demonstrate its ability to perform its function. The duration of test is specified in a detailed test procedure. The item is mounted on the vibration generator in a manner that is representative of its installation under service conditions. The vibratory forces are applied to each of the three major perpendicular axes independently unless symmetry justifies otherwise. Sufficient monitoring equipment must be used to accurately evaluate performance before, during, or after the test, depending on the nature of the item to be tested.

D.4.3 Sine-Beat Test

The test is made by inducing sine beats of peak acceleration corresponding to that for which the item is to be qualified, at the frequency and amplitude of interest. The duration and amplitude of the beat for each test frequency must be chosen to produce a magnitude equivalent to that produced by the particular building-element response, with appropriate damping factors. For a test at any given frequency, five beats of ten cycles per beat are normally used, with a pause between the beats so that no significant superposition of motion will result. Mounting of equipment and instrumentation is described in Sect. D.4.2.

D.4.4 Multiple-Frequency Test

The item is tested over the frequency range of 5 to 60 Hz at a maximum sweep rate of 2 Hz. The input at any given frequency is equal to at least the corresponding frequency of the response spectrum for the building element of interest for the operating basis earthquake (OBE). Section D.4.2 discusses the mounting of equipment and instrumentation.

D.4.5 Documentation

The test and analytical procedures and any modifications of the item must be documented, together with complete results of operational tests conducted during or after the vibration test, as applicable.

D.5 MATHEMATICAL ANALYSIS

Components or the complete system may also be qualified by a mathematical analysis. The objective of the analysis is to predict the stresses, displacements, and deflections that will develop in critical parts of the component or system as a result of the specified input or time-history motion applied at the base (anchor points) of the component or system by an earthquake. The problem is defined by the physical properties of the system to be analyzed; its mass, stiffness, and damping characteristics; and the time-varying accelerations, displacements, and relative velocity changes introduced at its foundation (anchor points).

If the mass of the component or system to be analyzed is small relative to the mass of the building element to which it is anchored, the supported component or system may be treated as a lumped-mass, multidegree-of-freedom system, having an input at its foundation (anchor points) equal to the motion of the building element to which it is attached (i.e., no interaction assumed).

If the natural frequency of the item (component or system) is less than 0.2 Hz or more than 40 Hz, the item may be analyzed statically. The seismic forces on each element of interest of the item are obtained by concentrating its mass at its center of gravity and multiplying it by the appropriate maximum floor acceleration. Operating, live, and dead loadings are added to the seismic loadings in their appropriate directions. Displacements may be the limiting factor and must be accounted for in the design analysis. The following damping values may be used:

Type of system	For SSE	For ½ SSE
Welded	5.0	2.0
Bolted	7.0	5.0

If the mass of the component or system is large relative to the mass of the building element to which it is attached, or if the item is not anchored rigidly to a building element, the interaction of the system on the building element must be considered; the system is dynamically analyzed as a multidegree-of-freedom mathematical model. The item (component or system) may be modeled as a series of discrete mass points connected by mass-free members, with sufficient mass points to ensure adequate representation of the item as it is supported in the building structure. The resulting system may be analyzed using the response spectra model analysis technique or a time-history (modal or step-by-step) analysis technique. A stress analysis is then made using the inertial forces or equivalent static loads obtained from the dynamic analysis for each vibration mode. If the response spectrum analysis technique is used, the seismic design stress may usually be obtained by taking the square root of the sum of the squares of the individual modal stresses; the absolute sum of the responses should be taken, however, for closely spaced, in-phase vibration modes. In the analysis, each of the two major horizontal directions is considered separately and simultaneously with the vertical direction in the most conservative manner.

The analysis must include an evaluation of the effects of the calculated stresses on mechanical strength, alignment (if critical to proper operation of the air cleaning system), and operational (functional) performance of the components and the system as a whole. Maximum displacements at critical points must be calculated and interference or plastic deformation determined and evaluated.

D.6 DOCUMENTATION

The selected method or methods of seismic analysis, mathematical models and their natural frequencies, input time-histories and corresponding response spectra, damping values, and allowable stress criteria must be shown in a safety analysis report, together with results of all tests and analyses. The documentation must give details which demonstrate that the item meets specified requirements when subjected to the seismic motion for which it is to be qualified. Analytical procedures should be described in sufficient detail to be readily auditable by persons knowledgeable in such analyses. Analytical and test results should be certified by a licensed professional engineer qualified in the analysis of such systems.